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Scientific paper

Ecological characteristics and ratings for soils of Arctic Canada

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Abstract: This paper presents results from the terrestrial research group from the Swedish-Canadian expedition "Tundra Northwest 1999" (TNW99). Sites were chosen with respect to the ecological states mesic and dry. Soils show a great variability with regard to local aspects. Elevated contents of organic matter ($>2\%$ TOC) are abundant, especially at mesic sites with full vegetation cover. C/N-values lower than 14 correspond with a dominance of annual plant species. Strong differences in the contents of oxalate extractable iron are observed. Most soils have low salt contents and react alkaline due to higher contents of carbonates with respect to their parent material. Soils are strongly influenced by climate conditions, some of them are enriched with salts, due to an influence of the sea shore in the neighbourhood. Surface layers show high amounts of bacteria, extremes are above 10^9 cells g^{-1}. All communities show mostly small sized organisms, and reveal low values of mean cell volumes and surfaces, and thus low biomass. The most important group of bacterial cells can be seen in small rod shaped cells (0.25–0.75 μm). A concept of ecological ratings is used to describe the regional and local differences. The TNW99 sites are compared to those from other locations from Arctic Canada taken from literature.

key words: Arctic soils, Canada, permafrost soils, ecological rating

1. Introduction

General descriptions of soils in polar systems have been carried out in both Arctic and Antarctic systems and summarised by *e.g.*, Bliss *et al*. (1981), Blume and Bölter (1996), Beyer and Bölter (2002), Kimble (2004). Most of these studies, however, focus on local aspects, but aspects of synoptic views of larger realms, like the Canadian Arctic, are rare.

This region (above the northern tree line) covers about 30% of Canada. It is a patchwork of individual islands with distinct habitats which forms distinct populations of plants and animals at scales of meters or below (Rieger, 1974). Most of the area of the Canadian archipelago receives less than 100 cm snow per year, higher amounts are only found for central (100–200 cm) and eastern (200–300 cm) Baffin Island (French and Slaymaker, 1993). Cryosols with permafrost within 1 or 2 m are the dominating soils. Its importance for global concern is given by the tundra environment which covers worldwide about 5.5% of the land surface (Brown *et al*., 1980).

This area with lowest temperatures and short growing seasons is one of the main carbon resources on earth, which accounts for about 14% of total C (Post *et al*., 1982; Gilmanov and Oechel, 1995). The actual high storages of carbon accumulated reflect the long time of imbalances between production and decomposition. Hence, these systems have attracted much attention for scientific projects on global warming.

The great extension of the Canadian Artic yields in a wide differentiation in terms of descriptions by geography, meteorology, or ecology. The major climatic regions of northern Canada have been split into 5 sections (Maxwell, 1981) with significant differences in temperature ranges, precipitation and net radiation (Bliss, 1997). Islands of the Canadian landscapes receive minimal precipitation, which results in their character of a polar (biological) deserts or semi-deserts. Such landscapes are typical for the high-arctic Queen-Elizabeth Islands (Bliss, 1981) with only poor soil development (Everett *et al*., 1981). Elevated landscapes are widely barren with no significant plant biomass. Other places, like the "oases", or more southern located regions are suited with richer plant life and animal populations (Elliott and Svoboda, 1994; Cockell *et al*., 2001). The islands form mostly gently sloped hills forming wide areas with favourable microclimate and thus prolonged plant growth as well as time for microbial activity. Further, this flat terrain in combination with a shallow active layer above the permafrost table prevents the rapid runoff of melt water keeping high soil moisture for long periods and thus forming the so-called mesic sites. These areas are covered by meadows with higher plants, soils can have a deep brown top layer which is penetrated by roots down to 30 cm or even more. Elevated areas become dry and are dominated by cushion-plant-lichen communities.

Tundra variability is due to the soil cover as well as to local climate regimes, which are responsible for cryogenic processes. Vegetation patterns and plant growth forms may change drastically within distances of few meters due to small-scale patterns of topography and related variables of hydrology and soil chemistry (Bliss, 1981; Bliss *et al*., 1984; Gebauer *et al*., 1995; Chapin *et al*., 1988). Such factors affect significantly parameters of soil biology and soil physics (Shaver and Chapin, 1991; Johnson *et al*., 1996; Cheng *et al*., 1998). Plant growth and distribution in the Arctic environments is strongly influenced by duration of the snow-free period, like the general constraints given by soil temperature, soil moisture and nutrient availability (Press *et al*., 1998).

Further, it is important that these data describe only the surface horizons. An inclusion of the deeper layers down to 1 m increases those stock values by a factor of 2.5 (Michaelson *et al*., 1996). Tussock tundra sites near barrow were identified as the most biologically inactive areas due to their low nutrient availability (Cheng *et al*., 1998). Microrelief shows control on community type at Alexandra Fiord (Batten and Svoboda, 1994) and in Alaska (Peterson and Billings, 1980), an effect, which has been attributed to drainage in response to relief patterns (Webber, 1978). Interactions between relief, permafrost, moisture and soils as well as their effects on vegetation patterns are described in various reports (*e.g*., Bliss *et al*., 1984; Edlund and Alt, 1989; Shaver and Chapin, 1991; Blume and Bölter, 1996; Cheng *et al*., 1998).

Gradients and differences between local aspects and individual habitats can be as large as between different regions. Variation in mineralogy of the parent material is much wider than pedological features (Pawlik and Brewer, 1975). However, correlations between soil mineral content and plant cover are hard to establish (Edlund, 1983). Dry sites are generally unfavourable environs for plant and animal life. Low temperatures and poor humidity in combination with elevated salt contents and intense UV-radiation hamper microbial life in the upper layers. Primary producers in these environs are mostly restricted to lichens, algae and few cyanobacteria, which provide some nutrients for heterotrophic organisms. High-Arctic environments show mostly well-drained soils (Rieger, 1974), a fact, which is true for most areas on mountain areas of our studies. Woodley and Svoboda (1994) further state that such areas often become xeric after snowmelt and are thus preferably covered by lichen assemblages rather than higher plants.

Soil formation is affected by local topographic, hydrologic and climatic features; cryoturbation leads to an unstable environment, which prevents the settlement of non-rooting plants (Tedrow, 1977). The dominant soil-forming processes in this area are cryoturbation, organic matter accumulation, physical and also chemical weathering, redoximorphism, and sometimes podzolization under moist and calcification together with salinization under dry conditions (Goryachkin *et al*., 2004). Effects of downward leaching are neglected under the influence of cryoturbation especially in the High Arctic. Well-developed soils which also show greater stability by roots and imbedded litter material are typical for oasis or mesic to wet sites (Muc *et al*., 1994).

The expedition “Tundra Northwest 1999 (TNW99)” was designed to perform a synoptic view within one season on biological features of the Arctic Canada (Grönlund, 1999; Molau *et al*., 1999; Erikson *et al*., 2003) along a latitudinal and longitudinal transect. The tundra soils of the TNW-transect reflect a wide range of soil-forming factors and processes. The sub theme “Biodiversity” was analysing soils, soil biota, and vegetation covers by lichens, mosses and higher plants at different scales. Further, a broad range of organisms were investigated by other projects involved in the Biodiversity theme, zoologists covered groups of mammals, insects, and collembolans. The variety of organisms allowed a study on patterns of variation in diversity, or the lack of it. The advantage of this expedition was the possibility to study a wide variety of organisms on the same spot, at the same time, using a standardized sampling technique sets. More details about the TNW99 expedition and its pedological and ecological results are presented by Bölter (2003) and Bölter *et al*. (2003).

2. Material and methods

Figure 1 depicts the locations 1–17 visited during of the expedition “Tundra Northwest 1999”. The cruise took place in July–August 1999 (leg 1: sites 1–9, July 2–28, leg 2: sites 10–17, August 4–30). Soil sampling was carried out at dry and mesic sites, which were identified at the landing sites due to features of the local vegetation cover. Distances between the dry and mesic sites were generally less than 1 km. The different patterns relate mostly to slight differences altitude, *i.e*., dry sites were located on hills, whereas the mesic sites were either at week slopes or in slight depressions.

Soil pits were dug to depths until permafrost and samplings were carried out with respect to soil horizons at appropriate depth layers. Samples (approx. 1 kg each) were

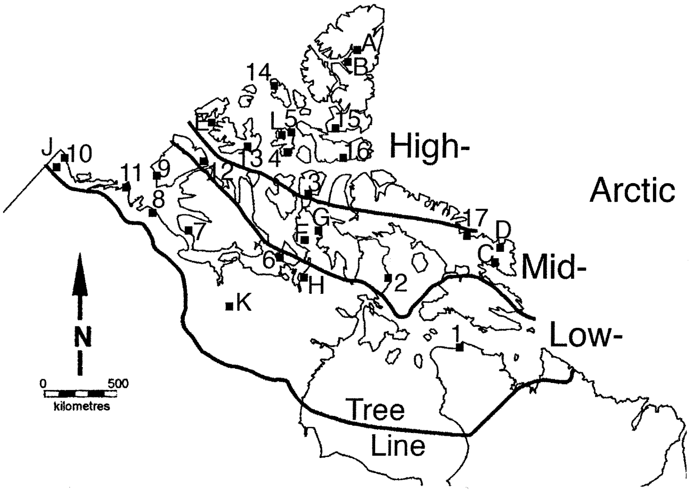

Fig. 1. Map of the Canadian Arctic and its ecological settings (after Tarnocai, 2004). The locations 1–17 were visited during the expedition TNW99 (leg 1: 1–9, leg 2: 10–17). The letters A–L refer to sampling sites of Tarnocai (2004), of which sites D, E, F, H, J, and L were selected for comparisons with our data.

taken with well-cleaned spatulas and placed into plastic bags. Storage until analyses was at $+4^{\circ}C$ for shipboard measurements, samples for laboratory analyses in Kiel were stored deep-frozen until use.

Soil descriptions were performed at the pit, samples for chemical and biological analyses were frozen and analysed in the laboratories in Kiel. Site and soil description were performed after FAO (1990); soil classification after ISSS/ISRIC/FAO (1998). Laboratory analyses of soils were performed after Schlichting *et al.* (1995), in brief:

- Texture analysis: sieve and pipette method after H_2O_2 and HCl extractions and Na-pyrophosphate-dispersion of fine soil;
- organic carbon (C_{org}): dry oxidation at 1200°C, coulometric CO_2 measurements and subtraction of carbonatic C; SOM (soil organic matter) $= C_{org} \times 2$.
- Loss in ignition (LOI): combustion of dry samples at 550°C, and calculation by weight loss;
- total nitrogen: N_t: Kjeldahl digestion;
- N_{min}: (=mineral nitrogen) extraction of NH_4 and NO_3 with $CaCl_2$, colorimetric measurement of NH_4 and NO_3;
- available or weatherable phosphorus: P_a (available phosphorous) extract with NH_4-lactate/acetic acid, P_v (extractable phophoprus with hot HCl after humus oxidation at 500°C), measurement colorimetric;
- carbonates: H_3PO_4 treatment at 80°C and CO_2 measurement like C_{org}, transformation into $CaCO_3$;
- available nutrients: exchange of Ca_a, Mg_a, K_a and Na_a with $BaCl_2$ at soil pH, pedogenic oxides (Fe, Mn, Al) by dithionite-citrate-bicarbonate extraction; measurements by AAS (atomic absorption spectroscopy);
- soil reaction: potentiometric measurement of pH ($CaCl_2$) at 1 : 2.5 (soil : water);

- electrical conductivity: measurement at 1 : 2.5 (soil : water) and transformation to the water content of the saturation extract after contents of clay and organic matter;
- bulk density and available water capacity: d_b and awc: dry weight and water content of 100 m*l* core samples at pF 1.8 and 4.2; or calculation of awc from texture, gravel and humus content;
- data on microbial organisms, bacterial counts, carbon, cell volume and related data for algae were estimated by epifluorescence microscopy and subsequent calculations (Bölter, 2001; Bölter *et al.*, 2002).

Here, we refer only to samples of leg 1 and we refer to soil depths 0–30 cm for which we assume most activity with respect to soil organic and inorganic matter. These descriptions are performed for two purposes, 1) an attempt to evaluate parameters, which are able to describe separations between the regions (Fig. 1), and 2) to establish thresholds for parameters according to an ecological rating system (Schlichting *et al.*, 1995), which has been adopted and applied to polar soils (Bölter and Blume, 2002; Blume and Bölter, 2004; Table 1).

Table 1. Assessments of ecological site conditions adapted for Polar Regions for 30 cm soil depth (after Schlichting et al., 1995, modified by Bölter and Blume, 2002).

rating	I very low	2 low	3 medium	4 slightly high	5 high	6 very high	7 extreme high
Sfp[1] months	< 0.75	1.5	3	6	9	12	
r.p.[2] . %	100	85	60	40	15	0	
awc[3] $L\ m^{-2}$	< 15	30	60	90	140	200	>
e.c.[4]	< 0.75	2	3	4	8	15	>
mS/cm	< 0.02	0.1	2.0	4.5	12	25	>
N_{min}[5] $g\ m^{-2}$	< 2	8	24	48	80	200	>
K_a[6] $g\ m^{-2}$	< 4	15	50	100	200	500	>
Ca_a $g\ m^{-2}$	< 2	5	15	30	60	150	>
Mg_a $g\ m^{-2}$	< 5	25	125	175	250	400	>
$P_v(P_a)$ $g\ m^{-2}$	< 0.2	0.5	1.0	2	4	8	>
SOM[7] $kg\ m^{-2}$	< 0.3	0.6	1.2	3	6		>
bact[8] $g\ m^{-2}$	< 5	15	40	60	80	95	>
feed[9] %							
oxygen availability[10]	poorly drained mostly water saturated		imperfectly drained			well drained	

[1] snow free period.
[2] penetrability by roots (mass % of stones + gravels, rock = 100%; mean of 3 dm.
[3] available water capacity (+groundwater if high groundwater table).
[4] e.c.: electrical conductivity: rating: 1 (nearly) not salty, 2–7 salty.
[5] N_{min}: inorganic nitrogen.
[6] index "a" for K, Ca, and Mg refers to its plant availability.
[7] SOM: soil organic matter (= $C_{org} \times 2$).
[8] bacterial biomass in g Cm^{-2} (rating of 1/2 microbial biomass after Machulla (1997), with an adaptation due to mean temperature of the vegetation period after Blume *et al.* (1991).
[9] feed activity, relative feeding % during 10 days in relation to offered food stripes (Törne, 1990).
[10] 1: Histosols (not folic), Histic Gleysols and Fluvisols; 2: Gleyic Planosols, Stagnic Gleysols; 3: other Planosols and Gleysols; 4: Vertisols; 5: Stagnic and gleyic subunits of other soils; 6 and 7: other soils.

Table 2. Ranges and median values of parameters used to identify the Arctic regions (see Fig. 1) and the mesic and dry sampling sites of the expedition TNW99 (for soil depth 0–10 cm).

	arctic region[1]	low		med		high	
	moisture	mesic	dry	mesic	dry	mesic	dry
parameter							
active layer (cm)	range	55- >105	80->100	35	65	40-50	45-50
	median (n)	(4)	(3)	(1)	(1)	45 (3)	47 (2)[2]
plant cover (%)	range	90-100	5-30	100	85	90-100	5-10
	median (n)	98 (5)	15 (3)	100 (1)	85 (1)	96 (3)	7 (2)
root depth (cm)	range	25-40	15-40	20	20	15-25	10-15
	median (n)	33 (4)	30 (3)	20 (3)	(1)	20 (3)	12 (2)
CEC[1] mmolc/kg	range	82-846	12-120	17-314	10-113	60-268	59-145
	median (n)	260 (6)	47 (4)	131 (3)	62 (2)	129 (7)	100 (4)
K (%)	range	0-2	2-6	0-7	1-10	0-6	1-9
	median (n)	1 (6)	4 (4)	4 (3)	5 (2)	2 (7)	3 (4)
Na (%)	range	1-3	2-15	1-15	2-19	1-4	2-4
	median (n)	2 (6)	9 (4)	7 (3)	10 (2)	2 (7)	3 (4)
Ca (%)	range	93-95	79-89	74-96	68-93	87-96	84-93
	median (n)	94 (6)	82 (4)	86 (3)	80 (2)	94 (7)	90 (4)
Mg (%)	range	1-4	4-8	2-3	3-4	1-6	4-5
	median (n)	3 (6)	6 (4)	3 (3)	3 (2)	2 (7)	4 (4)
pH ($CaCl_2$)	range	4.6-7.7	5.3-7.8	5.1-7.2	5.7-7.4	5.9-7.7	6.5-7.7
	median (n)	6.6 (6)	7.0 (4)	5.8 (3)	6.6 (2)	7.0 (7)	7.1 (4)
e.c.[2] (μS/cm)	range	39-294	22-207	56-260	15-235	83-216	103-172
	median (n)	182 (6)	105 (4)	142 (3)	125 (2)	161 (7)	147 (4)
$CaCO_3$ (%)	range	0.4-37.6	0.4-87.7	0.3-2.2	0.3-26.1	0.3-73.5	0.3-57.6
	median (n)	17.8 (6)	40.8 (4)	0.9 (3)	13.2 (2)	24.7 (7)	25.1 (4)
C_{org} (%)	range	2.8-12.5	0.1-1.7	2.1-5.6	0.6-2.0	0.8-9.7	0.6-1.9
	median (n)	5.6 (6)	0.8 (4)	4.1 (3)	1.3 (2)	3.2 (7)	1.5 (4)
C/N	range	13-34	12-26	12-17	10-21	9-87	6-14
	median (n)	19 (6)	17 (3)	15 (3)	10 (2)	23 (7)	10 (3)
LOI[2] (%)	range	5.3-60.5	2.6-65.0	12.0-18.8	9.6	3.2-56.4	3.8-7.7
	median (n)	25.0 (7)	15.7 (5)	15.0 (3)	9.6	20.7 (7)	5.7 (3)
N_t (mg/g)	range	2.0-4.7	0.3-1.4	1.2-4.7	0.3-2	0.9-2.8	0.9-5.5
	median (n)	2.9 (6)	0.7 (4)	2.9 (3)	1.2 (2)	1.6 (7)	2.4 (4)
P_t (mg/g)	range	0.2-0.9	0.1-0.3	0.3-0.6	0.4	0.2-0.6	0.4-1.2
	median (n)	0.5 (5)	0.2 (4)	0.4 (3)	0.4	0.4 (6)	0.7 (4)
Fe (mmol/kg)	range	14.5-82.2	1-36	14.1-37.6	4.9	6.3-46.1	4.5-19.7
	median (n)	36.7 (5)	18.6 (4)	27.6 (3)	4.9	27.3 (7)	13.8 (3)
Mn (mmol/kg)	range	0.2-7.0	5.0-6.7	0.4-14.0	0.3	0.2-4.4	0.6-2.3
	median (n)	2.1 (5)	5.8 (2)	5.3 (3)	0.3	1.8 (7)	1.5 (3)
Al (mmol/kg)	range	15.9-28.9	3.5-25.4	33.3-66.0	16.6	7.1-39.6	8.2-26.6
	median (n)	20.5 (5)	17.1 (4)	45.5 (3)	16.6	18.3 (7)	16.3 (3)

[1] CEC: cation exchange capacity

[2] LOI: loss on ignition

Table 2. Continued.

	arctic region[1]	low		med		high	
	moisture	mesic	dry	mesic	dry	mesic	dry
parameter							
TBN[a]	range	0.27-1.21	0.17-1.67	0.32-0.85	0.23	0.16-2.49	0.10-0.66
(10^9 g^{-1})	median (n)	0.61 (7)	0.59 (5)	0.55 (3)	0.23	0.81 (7)	0.38 (3)
BBM[b]	range	1.16-5.44	0.57-6.25	0.56-4.48	0.87	0.5-10.73	0.18-1.80
(μg C g^{-1})	median (n)	2.52 (7)	2.10 (5)	2.16 (3)	0.87	3.33 (7)	1.15 (3)
MCV[c]	range	33-45	28-38	18-52	29	31-51	19-39
(10^{-3} μ^3)	median (n)	40 (7)	34 (5)	33 (3)	29	38 (7)	28 (3)
MBS[d]	range	0.49-0.62	0.44-0.54	0.30-0.70	0.44	0.46-0.68	0.33-0.55
(μm^2)	median (n)	0.56 (7)	0.50 (5)	0.48 (3)	0.44	0.54 (7)	0.44 (3)
TAN[e]	range	0-2.38	0-1.58	0-1.33	0	0-1.12	0
(10^6 g^{-1})	median (n)	0.89 (7)	0.32 (5)	0.44 (3)	0	0.49 (7)	0 (4)
ABV[f]	range	0-1310	0-171	0-576	0	0-513	0
(10^6 μ^3)	median (n)	271 (7)	34 (5)	192 (3)	0	165 (7)	0 (4)
MAS[g]	range	0-529	0-216	0-462	0	0-662	0
(μm^2)	median (n)	198 (7)	43 (5)	154 (3)	0	246 (7)	0 (4)

[a] total bacterial number; [b] bacterial biomass-C; [c] mean bacterial cell volume; [d] mean bacterial surface; [e] total algal number; [f] total algal biovolume; [g] mean algal surface

3. Results

The results of this study show only to some extent the possibility to establish clear separations of the ecological zones, which are mainly due to general climatic relationships (Fig. 1), but may be superimposed by local aspects of altitude. This is due to the wide overlapping of the data spans of the parameters (Table 2) of the regions and of the soil moisture settings mesic-dry. Using the median values and the spans, some separations between the zones can only be performed at a similar moisture level (mesic or dry) or for these levels. This is especially true for plant cover; as root depth shows some correlation to the climatic gradients.

SOM shows a pattern, which allows differentiating between the mesic and dry sites, but not between the zones. The C/N-ratio shows highest values at mesic sites in the high Arctic. Total nitrogen (N_t) also points to higher contents in the high Artic zone, which may be attributed to residual N due to less plant growth in this region. This pattern is also visible for total phosphorous. For microbiological characters (total count, bacterial biomass, mean cell volume and total cell surface) differentiations become only possible for moisture settings, *i.e.*, for plant growth and thus probably for available organic matter.

The ecological ratings low, medium and high according to the thresholds given in Table 1 renders medium to high levels of most characteristics for the mesic sites, and low to high levels of nutrients and bacterial carbon (Table 3). It can be seen that the ratings show levels of low (K, Mg), medium (awc, P_t, C_{bact}), slightly high (C_{org}) and high (Ca) for the dry sites. Shifts to higher categories occur for K and Mg, Ca, C_{org} and C_{bact} at the mesic sites, awc and P_t are not influenced.

Table 3. Ratings of soils by their ecological data of the upper 30 cm for awc (available water capacity) for mesic (m) and dry (d) sites of TNW99 stations 1–9 in the high, mid and low Arctic. Nutrients were done for total soil (incl. skelet material) and for postulated fine soil bulk density of 0.2 kg L^{-1} (for >40% TOC, 0.4 for 15–40%), 1.0 kg L^{-1} for loamy and/or humus (2–15% TOC) and 1.2 kg L^{-1} for other soil horizons; all data are recalculated to SI-units; for methodical details see Schlichting et al. (1995) and Bölter et al. (2002); numbers in brackets refer to the ecological state (Table 1).

Site	oxygen[1]	e.c. mS/cm	skelet %	awc L m^{-2}	K g m^{-2}	Ca g m^{-2}	Mg g m^{-2}	P_t g m^{-2}	SOM kg m^{-2}	C/N	C_{bact} mg m^{-2}
3* m high	(6)	1.0 (2)	30-50 (4-5)	59 (3)	11 (3)	540 (7)	6.1 (3)	85 (3)	24 (7)	11	397 (5)
3 d high	(6)	1.2 (2)	30-50 (4-5)	49 (3)	13 (3)	600 (7)	15 (3)	71 (3)	7.3 (6)	10	150 (4)
4* m high	(4-5)	0.6 (1)	5-10 (6)	57 (3)	12 (3)	380 (6)	5.9 (3)	175 (4)	9.2 (7)	13	172 (4)
4 dry high	(6)	1.2 (2)	50-70 (3-4)	34 (3)	4.9 (2)	170 (5)	6.3 (3)	74 (3)	3.8 (5)	16	42 (2)
2* m mid	(4-5)	0.5 (1)	<5 (6-7)	62 (4)	20 (3)	120 (5)	1.9 (1)	89 (3)	7 (6)	15	108 (3)
2 d mid	(6)	0.7 (1)	10-30 (5)	53 (3)	9.4 (3)	41 (3)	0.9 (1)	72 (3)	2.7 (4)	32	149 (4)
1* m low	(6)	0.4 (1)	30-50 (4-5)	21 (2)	4.1 (2)	150 (5)	1.4 (1)	69 (3)	2.8 (5)	13	170 (4)
6* m low	(6)	1.0 (2)	>70 (2-3)	9 (1)	3.2 (2)	290 (6)	7.9 (3)	43 (3)	4 (5)	34	66 (3)
6d low	(6)	1.2 (2)	>70 (2-3)	9 (1)	0.5 (1)	110 (5)	0.4 (1)	5 (2)	0.5 (2)	22	27 (2)
7* m low	(6)	1.3 (2)	10-30 (5-6)	75 (4)	10 (3)	530 (7)	14 (3)	44 (3)	13 (7)	12	137 (4)
7 d low	(6)	2.0 (2-3)	10-30 (5-6)	60 (3)	17 (3)	134 (5)	7.7 (3)	48 (3)	1.4 (4)	11	158 (4)
8* m low	(6)	2.0 (2-3)	10-30 (5-6)	60 (3)	15 (3)	510 (7)	10 (3)	56 (3)	9.2 (7)	9	97 (3)
8 d low	(6)	1.2 (2)	20-40 (4-5)	54 (3)	7.3 (2)	134 (5)	3.3 (2)	32 (3)	1.7 (4)	10	64 (3)
9 mc low	(6)	1.5 (2)	5-10 (6)	80 (4)	21 (3)	1340 (7)	37 (5)	122 (3)	23 (7)	13	319 (5)
9 d low	(6)	0.9 (2)	50-70 (3-4)	27 (2)	8 (2)	166 (5)	8.2 (3)	36 (3)	3.1 (5)	12	18 (1)
Mesic sites	mean rating			3 med	3 med	6 v.high	3 med	3 med	6 v.high		4 sl.high
Dry sites	mean rating			3 med	2 low	5 high	2 low	3 med	4 sl.high		3 med

Table 3. Continued.

General site descriptions:

*1 Skeleti-gelic Cambisol (albic), very weak frost pattern of moraine deposit on granite; 100% plant cover; 60 m a.s.l.; m-s: 3-4, fr: 65 cm; °C: 3

*2 Stagni (d: Hapli)-turbic Cryosol (m: eutric arenic, d: dystric); polygons on moraine deposit, 2m: 92%, 2d: 85% plant cover, resp.; 2m: 90, 2d: 140 m a.s.l., resp.; m-s: 1-2, fr m: 35, d: 65 cm, resp.; °C: 2m: 2, 2d: 1.5, resp.

*3 Calcari-turbic Cryosol (chromic sceletic) with polygons on moraine till; 3m: 95, 3d: 10% plant cover; 3m: 40, 3d: 85 m a.s.l.; 3m: 2, 3d: 1-2 m-s, 3m: 40, 3d: 55 cm fr; 3m: 2, 3d: 1-2°C.

*4 Stagni (d: skeleti)-turbic Cryosol (m mollic calcaric, d calcic) with polygons on moraine till; 4m: 100, 4d: 5 % plant cover; 4m: 110, 4d: 150 m a.s.l.; 0-1 m-s:, 4m: 50, 4d: 45 cm fr; 4m: 0.2, 4d: 0.1°C.

*6 Skeleti-leptic (d haplic) Cryosol (calcaric); polygons on moraine (d fluvioglacial) sands on limestone; 6m: 95, 6d: 5% plant cover; 6m: 5, 6d: 10 m a.s.l.; m-s: 3, 6m: >50, 6d: 80 cm fr; 1.5°C.

*7 Humi-mollic (d Haplic) Cryosol (calcaric); humocks (d stone stripes) on moraine till; 7m: 90, 7d: 10% plant cover; 7m: 180, 7d: 200 m a.s.l.; 1-2 m-s:, 7m: 40, 7d: >100 cm fr; 2.5°C.

*8 m Molli-gelic Cambisol (calcaric), d Calcari-gelic Regosol (skeletic) on moraine till; 8m: 90, 8d: 2% plant cover; 8m: 80, 8d: 110 m a.s.l.; 8m: 4, 8d: 3.5 m-s; 8m: 105, 8d: >100 cm fr; 8m: 5, 8d: 4.5°C.

*9 Molli-turbic (d Skeletic-haplic) Cryosol (m humic calcaric, d calcaric); polygons on moraine till; 9m: 98, 9d: 30% plant cover; 9m: 250, 9d: 290 m a.s.l.; 9m: 2, 9d: 1.5 m-s; 9m: 55. 9d >100 cm fr; 9m: 3, 9d: 2.5°C.

(a.s.l. above sea level, m-s: months without snow; fr permafrost in cm; °C: mean annual temperature during the snow free period, more details on sites and its properties on soils, vegetation and soil organisms are presented in Eriksen et al. (2003), Bölter et al. (2003) and Bölter (2003)

4. Discussion

The arctic tundra and desert environments have been studied widely by several authors in the past from different perspectives, *e.g.*, meteorology, botany, and soil science and yielded in many categories with the aim to set up geographical boundaries for general and specific purposes (for reviews see Kimble, 2004). Since some decades, global warming is changing this environment at many places. Thus, soil chemical as well as soil biological processes and soil development have attracted new research into this environment. Soils as an archive of life and chemical processes play an important role for monitoring; they are tools in observing changes and new states, which can be compared to former situations and elucidate ecosystem changes, *e.g.*, Rosswell and Heal (1975), Tedrow (1977), Brown *et al.* (1980).

Nevertheless, it was difficult to find studies with an similar broad task as the TNW 99 and sites analyzed in a similar way like ours. The publications of Tarnocai and Smith (1992) and Tarnocai (2004) had this task and were therefore use mainly for comparison with our data. Figure 1 depicts not only the sites 1–17 of the Tundra Northwest Expedition 1999 (TNW99) but also some sites sampled and analysed for soil properties by Tarnocai (2004), locations A–L. As these sites are located next to each other and show comparable information, they have been chosen partly for direct comparison (sites D, E, F, H, J and L); site H was split into a vegetated and a non-vegetated part (Hv, Hn) (*cf.* Figs. 2. 3. 4, site DK-1, in Tarnocai, 2004). From another study (Tarnocai *et al.*, 1993) we chose three further sites (T1–T3), which are located on the mainland, (Table 4):

T1: (Reference No.: 1-1993) 68° 18′57″N, 133° 25′51″E, Mackenzie Valley, alt. 100 m, polygonal peat plateau, large polygons, mesic sedge peat, wet, dwarf shrubs, mosses,

Table 4. Summarized site conditions taken from Tarnocai (2004), sites E–J for high, mid and low Arctic region (Fig. 1), and for sites T1–T3 (Tarnocai et al., 1993); for calculations and abbrevations see Table 3; numbers in brackets refer to the assessment of the ecological state (Table 1).

Site	oxyg. availab	e.c. mS/cm	skelet %	awc $L\ m^{-2}$	K_a $g\ m^{-2}$	Ca_a $g\ m^{-2}$	Mg_a $g\ m^{-2}$	SOM $kg\ m^{-2}$	C:N	Roots[1]
E* (high)	(5)	5 (5)	5-10 (6)	72 (4)	52 (5)	1600 (7)	160 (7)	27 (7)	11	
L* (high)	(1)	No (1)	0 (7)	150 (6)	92 (6)	746 (7)	107 (6)	60 (7)	>100	
D* (mid)	(2-3)	No (1)	0 (7)	55 (3)	40 (4)	246 (6)	47 (5)	47 (7)	39	
F* (mid)	(6-7)	2.2 (3)	3 (5)0	50 (3)	46 (4)	325 (6)	72 (6)	30 (7)	13	
H*(v) (low)	(6)	1.8 (2)	30 (5)	50 (3)	12 (3)	51 (4)	9.2 (3)	6.1 (6)	17	
H*(n) (low)	(7)	1 (2).	50 (4)	24 (2)	7.2 (2)	22 (3)	4.2 (2)	0.3 (2)		
I* (low)	(2-3)	0.2 (1)	5-10 (6)	75 (4)	15 (3)	547 (7)	107 (6)	34 (7)	25	
T1* (low)	(1-2)	?	0 (7)	180 (6)	1.8 (1)	885 (7)	102 (6)	56 (7)	25	10
T2* (v) (low)	(2)	<0.75 (1)	3 (6-7)	66 (4)	16 (3)	127 (5)	27 (4)	44 (7)	55	35
T2* (n) (low)	(3)	<0.75 (1)	5 (6)	21 (2)	14 (3)	101 (5)	19 (4)	36 (7)	20	2
T3* (v) (low)	(5)	<0.75 (1)	35 (5)	45 (3)	9.3 (3)	164 (5)	51 (5)	2.2 (5)	15	35
T3* (n) (low)	(6)	<0.75 (1)	45 (4)	32 (3)	7.8 (2)	138 (5)	34 (5)	1.6 (4)	13	2
mean rating				4 sl. high	3 med.	6 very high	5 high	6 very high		

[1]root depth (cm)

General site desriptions:

D: Baffin Island, Umbri-gleyic Cryosol of eolian sand with ice wedge polygons; *Dryas* tundra; fr: 26 cm; site code in Tarnocai (1993): 12-96-9.

E: Melville Island, Molli-turbic Cryosol of colluvium with non sorted circles, moss sedge tundra; fr: 40 cm; site code in Tarnocai (1993): 12-81-26.

F: Melville Peninsula, Hapli-turbic Cryosol of stony till of earthy hummocks; moss lichen tundra; site code in Tarnocai (1993): DC-3.

H: Nunavut North, Dystri (n: Skeleti)-turbic Cryosol of stony till with non sorted circles; v: lichen shrub tundra, n: no vegetation; fr: 80 cm; site code in Tarnocai (1993): DK-1.

J: Nunavut North, Stagni-turbic Cryosol of colluvium with earthy hummocks; *Ericaceous* tundra; fr: 57 cm; site code in Tarnocai (1993): Y60.

L: Bathurst Island, Mesi-gelic Histosol of peat with hummocks; no vegetation; fr: 25 cm; site code in Tarnocai (1993): DB-3.

T1: Mackenzie Delta, Hemi-cryic Histosol of peat with large polygons; tundra of dwarf shrubs; 100 m a.s.l.; m-s: 5; fr: 52 cm; °C: 7.

T2: Richardson Mountains, Turbi-histic (n Stagni-turbic) Cryosol of clayey colluvium; v: *Eriopherum* tundra, n: no vegetation; 760 m a.s.l.; fr: v: 67 n: 48 cm.

T3: Central Yukon, Hapli-(n Skeleti)-turbic Cryosol of glacial till w. non-sorted circle; v alpine shrub tundra, n no vegetation; 1219 m a.s.l.; fr: > 110 cm.

lichens, hemi-cryic Histosol;

T2: (Reference No.: 9-1993) 66°42′59″N, 136°21′11″E, Richardson Mountains, alt. 760 m, pediment slope, clayey colluvium, wet, *Eriopherum* tundra, T2v (with vegetation cover): Turbi-cryic Cyosol (stagnic), T2n (without vegetation cover): Stagni-turbic Cryosol (dystric);

T3: (Reference No.: 22-1993) 64°32′50″N, 138°14′2″E, Central Yukon, alt. 1219 m, undulated moraine blanket, glacial till, non sorted circles, moist, alpine shrub tundra, Typic Cryaquept, (v: with vegetation cover = Hapli-turbic Cryosol; n: no vegetation cover = Skeleti = turbic Cryosol).

These soils of the TNW transects as well those from Tarnocai's (2004) study reflect a wide range of soil forming factors and processes, which show relevance by their soil properties to our sites. The temperature and precipitation gradient across this area shows a wide range and leads to very different local processes (Bliss, 1997), which depend on water availability, energy input and parent material. These items control mainly soil development, but it renders difficult to obtain all these parameters for detailed process descriptions for all sites. Generally, water is not limited for plant growth due to low evaporation rates, although low levels of awc at sites Hn and T2n (Table 4) indicate potential water stress at these sites. Further, low amounts of plant available potassium (*e.g.*, sites Hn and T3n) due to low pH concomitant to low amounts of humus and high stone contents have to considered as growth limiting factors. Plant available calcium was not found below thresholds for plant growth. Problems might occur for plant available magnesium at site H due to sandy texture and low CEC value.

Surface temperatures may easily exceed 15°C during sunny days (Nams and Friedman, 1994; Bölter, 1999) and thus promote growth of roots, decomposition of organic matter and chemical weathering. On the other hand, cryotrubation hampers rooting, as monitored for Turbic Cryosols; rooting at sites Hn and T3n is also limited by elevated stone contents.

Both, small scale local patterns, like mesic and dry, which were main topic as well as large scale climatic conditions pose their signature on soil properties and related soil biology. This becomes mostly evident for the cation exchange capacity as well as for properties which are involved in biological cycles (*e.g.*, C_{org}, SOM, C/N). Generally, mesic sites show high amounts of SOM due to hampered degradation rates. However, parameters which can be used to differentiate between regions or ecological situations (mesic, dry) are rare; these are only plant cover, P_t, N_t, C_{org} and to some extent the descriptors of the microbial community (Table 2). Mostly, the soil biological properties are better useful to distinguish between mesic and dry sites rather than between the geographical separations. This makes it difficult to gain large scale data on area bases if there are no clear data on this kind of differentiation or the plant cover which is basis for these terms.

As such storages of organic matter in Arctic tundra environments have become a focus point since the hypothesis that the tundra changes from a CO_2-sink to a CO_2-source due to global warming (Oechel *et al.*, 1993, 1995; Waelbroeck *et al.*, 1997). But even the C_{org} data of the dry sites show C-contents between 0.5 and 7.3 kg m^{-2}, the data from mesic sites reveal 2.8 and 24 kg m^{-2} (Table 3), the comparable data from Table 4 show 0.3 to 56 kg m^{-2}. Close relationships to microbial biomass and related parameters can be established (Tables 2, 3), although this material was not analyzed in further detail. Similar ranges could also be monitored between wet and dry tundra sites, coastal plains and alpine slope soils. Thus, different tundra types as well local peculiarities determine C-accumulation rates and stocks (Post *et al.*, 1982; Oechel and Billings, 1992; Tarnocai and Smith, 1992; Michaelson *et al.*, 1996; Bockheim *et al.*, 1998). The amounts of inorganic nutrients are generally low, which holds especially true for nitrogen, even maximal data do not exceed 5.5 mg g^{-1} (Table 2).

Under the assumption of $d_B = 0.8$ and a soil depth of 30 cm, this just comes up to 600 g m^{-2}. Phosphorus yields even lower values, in maximum an amount of 175 g m^{-2} (Table 3) was found. Such low nutrient levels were found to hamper primary production as well as decomposition (Heal *et al.*, 1981; Bliss *et al.*, 1984; Cheng *et al.*, 1998). Data on N and P entering the system via precipitation are rare; at Barrow the input of N was found to be 23 mg m^{-2} in 120 mm precipitation (Alexander, 1974). Further, horizontal runoff during snowmelt leads to a net loss of nutrients, this can be seen as a main effect for nutrient depletion of Arctic soils (Gersper *et al.*, 1980; Ryden, 1981), and remaining nutrient are only poorly available for plants.

Microbes are another aspect for the state of N in the tundra soils. On the one hand they have been found as important input factors via N_2-fixation (Gersper *et al.*, 1980; Bliss, 1997). On the other hand denitrification may cause significant losses, when the soils get wet and deficient in oxygen, as found for several samples in Tarnocai's study (Table 4) for Aquorthels and loamy Turbels. Oxygen deficiency may occur after snow melt or above the permafrost layer. This is relevant for sites I, T2n (Stagni-turbic Cryosols) and sites L and T1 (Histosols). However, tundra soils of mesic and dry environments are well aerated; thus, denitrification is of minor importance. This has been indirectly documented by Bunnell *et al.* (1980) who found only 5% of culturable bacteria as denitrifiers.

High cation exchange capacity (Table 2) can be mainly related to high amounts of Ca (ratings high to very high (Tables 3 and 4). For soils at Ellesmere Island (Alexandra Fiord, Woodley and Svoboda, 1994; Muc *et al.*, 1994), this was found to maintain seed germination in combination with prolonged favourable vegetation growth. Highest values can be monitored for mesic sites (Table 2), probably in relation to elevated contents of humics. Dry sites also show lower levels of available K, which is probably due to lower pH values and humus contents.

Our data on bacterial biomass (Table 3), which range between 18 and 397 mgCm^{-2} can be related to other reports from such soils. Direct comparisons with other studies, however, remain difficult and can only indirectly be confirmed by comparable data on number (*e.g.*, Bunnell *et al.*, 1975, 1980) and the general low size. Just in top centimetres of wet tundra at Barrow Bliss (1997) reports values of 12–20 gm^{-2} for total microbial biomass.

The data of our study on the tundra soils presented here, including those of Tarnocai (1993, 2004), have shown that the tundra environments in the Canadian Arctic are extremely diverse and that local and small scale differences dominate the large scale divisions. Dominant for this pattern is the local vegetation, which in turn is mainly a result from local geographical factors like aspect, slope or altitude. Permafrost depth is of special concern as it obviously controls rooting depth and thus limits the spread of shrubs and other small woody plants. Permanent roots increase soil organic matter and humic material, an important link for microbial life and further soil development.

The concept of an ecological rating was used to understand the strong differences in kind and intensity of vegetation cover and its influences on soil ecology. Further studies on its overall controlling factors, like snow cover, length of apparent growth season and details on hydrology are needed to get more insight into the functioning of the arctic systems.

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